

# FIELD-OPERABLE MICROCONNECTIONS USING AUTOMATICALLY-TRIGGERED LOCALIZED SOLDER-BONDING

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## ABSTRACT

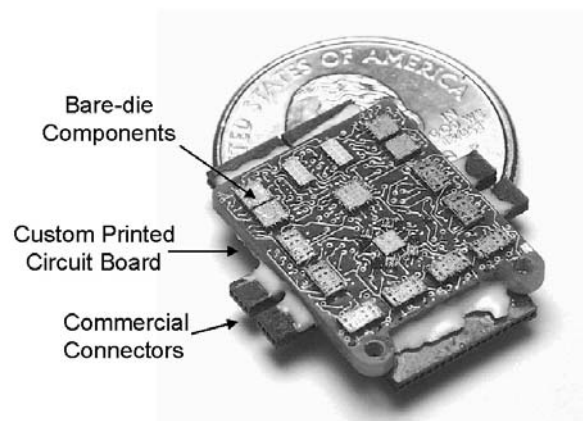
This paper presents an approach to realizing high-density electrical and mechanical connections to delicate microstructures in the field. “Smart” pads automatically detect proper contact alignment and activate a local heating element to create solder bonds between the pads and the pre-soldered lead tabs of a miniature flexible cable. The bonds occur in 350ms and result in less than  $10\Omega$  of series resistance between the cable and the pad. Connections have been demonstrated with lead-pitches as small as  $100\mu\text{m}$  and connection areas of less than  $0.375\text{ mm}^2$  per pad. The pad areas are fabricated with a five-mask circuit-compatible process. The flexible ribbon cables are made of polyimide with copper conductors. This work represents the first use of localized solder-bonding for making connections between microstructures and silicon substrates.

## INTRODUCTION

Microelectromechanical sensors and actuators as well as circuits for interfacing, control, and communications have matured significantly in recent years. In order for this technology to have a pervasive impact, however, the diverse electronic and microelectromechanical devices must be integrated, interconnected, and packaged to build viable microsystems. These microsystems will be widely used in environmental and biological monitoring, implantable medical devices, and miniature robotics. Many applications require the microsystems to be extremely small in order to minimize intrusion on the measurement environment. Certain applications also demand the ability to connect and disconnect delicate microstructures in the field, where complex assembly equipment is unavailable. For instance, a biologist may need to swap damaged off-board sensors in an insect-mounted microsystem without removing the system and returning to the laboratory.

Figure 1 shows a hybrid microsystem developed for monitoring/controlling insects for biomimetic studies leading toward the development of legged robots and “biobots” [1,2]. The system contains signal-conditioning circuits for amplifying and multiplexing sensor data from off-board neural probes and mechanical sensors. Although this system is sufficient for use with some insects, its size is

prohibitively large for many others. Approaches to shrinking such systems include monolithic circuit integration, reducing interconnect area by using silicon-based multi-chip modules, and implementing advanced packaging ideas such as folding platforms or three-dimensional assemblies. An important need in further reducing the size of such microsystems is improved technology for connecting sensors to the platform using minimal area. The mechanical connectors around the perimeter of the platform shown in Figure 1 enable sensors to be connected and disconnected manually; however, they consume an inordinate amount of board area. New developments in connector technology are necessary in order to realize smaller systems.



*Fig. 1: A hybrid insect-monitoring microsystem populated with commercial connectors for off-board sensors.*

Any new microconnection approach should enable direct connections from microstructures to silicon platforms without any specialized bonding equipment. It should also permit non-destructive disconnect and be built using a circuit-compatible fabrication process. This paper presents solder-based microconnections in which the bonding pad area automatically detects contact and initiates bonding by triggering localized heating of solder. This approach requires very little force and no equipment beyond a positioning tool or manipulator. Figure 2 illustrates a system that implements such microconnections along with some of the aforementioned approaches to shrinking the size of microsystems.

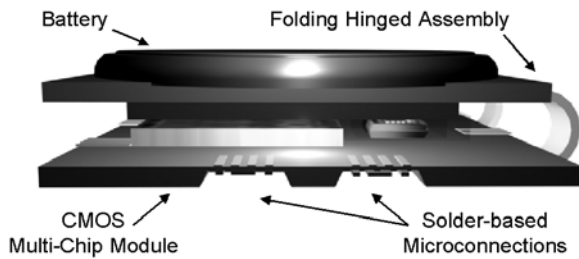


Fig. 2: A microsystem using solder-based microconnections, a folding silicon platform, and both hybrid and monolithic circuit integration.

## A SOLDER-BASED APPROACH TO MICROCONNECTIONS

Solder has long been used in electronic assembly to mechanically and electrically secure packaged components to printed wiring boards. Eutectic metal-alloy solders are designed to have low-temperature melting points in order to minimize the temperatures to which components are exposed. Components can be easily removed by withdrawing them while heating the bonding areas. Thus, the use of solder-based interconnects has a number of attractive features. However, traditional soldering methods pose several problems. Sensors and other microstructures are increasingly delicate and can be easily damaged or destroyed, both thermally and mechanically. Use of soldering irons or hot-air tools that are common in the macro-world is not always possible in the micro-domain. For example, using insect-mounted “backpack” microsystems for gait studies requires connections to leg strain gauges and EMG wires in the field; heating the platform to bonding temperatures with a soldering iron or reflow oven is precluded. For this and many other applications, a different approach to solder connections is necessary.

Many of the problems associated with external heating can be avoided by building heaters into the platform to heat the pad areas only. Cheng and Lin [3] have exploited this concept for silicon-to-glass bonding using localized heating of indium solder. For microconnections, heat can be applied directly under metal contact pads on a silicon substrate. When a device with pre-soldered lead tabs contacts the heated pads, the solder melts and establishes the desired bonds between the lead tabs and the pads. By confining the heated region to a very small area using thermal isolation, relatively low power is consumed, and the operation of neighboring devices on the wafer is not affected.

If solder bonding is to be useful for microconnections, the technology must be scalable to sub-millimeter dimensions. Solder has rarely been used for lead-pitches less than 1mm, and many applications have much less

stringent size requirements. Recently, solder balls for flip-chip bonding and chip-scale packages have been used commercially at pitches as small as 0.75mm [4]. Harsh and Lee [5] have used surface-area minimization of solder during melting for MEMS self-assembly. They report experiments and simulations indicating that the physical behavior of solder should remain consistent with scaling, even to sub-micron dimensions. This work suggests that solder should behave predictably on the scale 25 $\mu$ m to 500 $\mu$ m – the regime of interest for microconnections to components such as MEMS sensors. Also, solder’s tendency to coagulate and draw structures together is potentially beneficial in microconnections.

## DEVICE DESIGN AND OPERATION

The microconnection approach is designed to exploit the properties of solder bonding to produce automated, high-density connections to delicate microstructures in the field. A series of contact pads automatically detects proper alignment and placement of multi-lead ribbon cables and triggers localized solder melting between the pads and metal lead tabs on the cable to form electrically and mechanically stable connections. The structure consists of a thermally-isolated silicon island supporting a polysilicon heater and multiple interdigitated metal contact pads (Figure 3). The pads are designed to interface with flexible polyimide ribbon cables having metal lead tabs pre-coated with solder or plated with a suitable eutectic alloy.

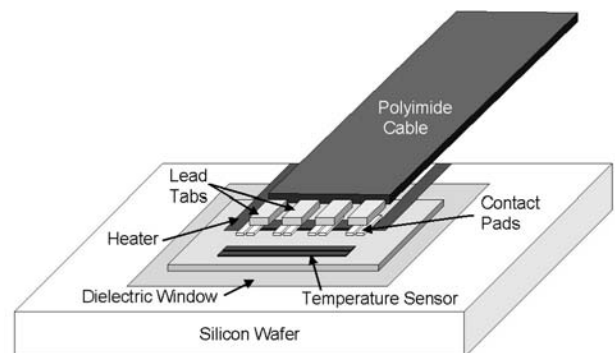


Fig. 3: Diagram of the micromachined microconnection approach with multi-lead contacts between a series of pads and a polyimide-based ribbon cable.

When a lead tab closely approaches a pad, its presence is detected by the impedance change between the interdigitated pad regions. When contact is detected in all bonding areas, a current pulse is directed to the polysilicon heater, causing the solder to melt and solidify, forming stable electrical and mechanical bonds between the cable leads and the pads (Figure 4). During a subsequent current pulse, the solder re-melts, and the cable can be withdrawn for replacement. Contact detection and triggering of the heater can be automated to enable connections by simply touching the cable leads to the pads and waiting momentarily for the bonds to be formed.

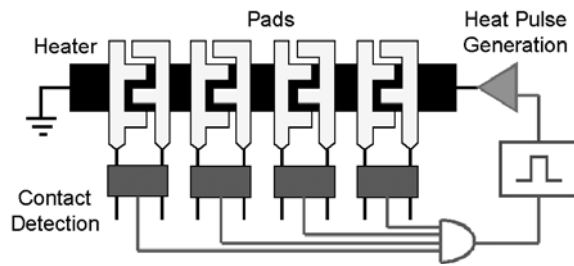


Fig. 4: Contact detection and heater-triggering scheme.

## DEVICE FABRICATION

Microconnection structures with contact pitches of 400 $\mu$ m, 200 $\mu$ m, and 100 $\mu$ m were fabricated using a five-mask circuit-compatible bulk-micromachining process [6]. The process begins by diffusing boron 15 $\mu$ m deep into a p-type silicon substrate to form rectangular p<sup>++</sup> regions. Next, layers of SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub>, and SiO<sub>2</sub> are sequentially deposited using chemical vapor deposition (CVD). A layer of CVD polysilicon is deposited over the dielectrics and is dry etched to define heater strips and interconnects. After deposition of an upper stack of stress-compensating dielectrics, Cr-Au is sputtered and patterned to form contact pads and metal lines. Finally, windows are etched through dielectrics on the backside of the wafer, and the wafer is wet-etched in tetramethyl ammonium hydroxide (TMAH) or ethylene diamine pyrocatechol (EDP). These etchants effectively stop on SiO<sub>2</sub>, p<sup>++</sup> silicon, and <111> crystal planes in silicon. Therefore, the etching forms pyramidal pits and leaves thermally-isolated p<sup>++</sup> silicon “islands” suspended from the dielectric membrane on the front side of

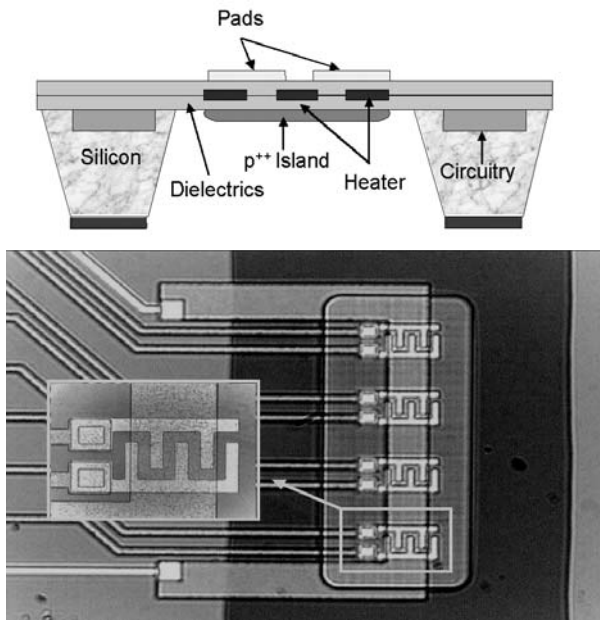


Fig. 5: a) Cross-sectional diagram of a bonding area (above), and b) Photograph of the bonding area with an inset showing a single contact pad.

the wafer. Figure 5a shows a cross-section of the bonding area, and Figure 5b shows a photograph and close-up view of a single interdigitated pad.

To interface with the pads, miniature flexible ribbon cables with pre-soldered lead tabs were fabricated with pitches corresponding to the contact pad spacings. A four-mask process is used to build polyimide cables with electroplated copper lines [7]. A silicon carrier wafer covered with thick sacrificial oxide is spin-coated with photo-definable polyimide and the cable shapes are patterned into this layer. A Ti-Cu seed layer is sputtered over the entire wafer, and thick photoresist is patterned for an electroplating mold [8]. After electroplating 15 $\mu$ m of copper, the photoresist and seed layer are removed, leaving plated copper lines on the polyimide cables with lead tabs extending beyond the ends of the cables. A second layer of polyimide, which is also patterned with the cable shapes, encapsulates the metal lines. Indium or lead-tin solder is electroplated on the lead-tabs using another thick photoresist mold. Alternatively, solder can be manually applied to the lead-tabs of released cables by dipping them in molten lead-tin or indium solder. The cables are released from the wafer by etching the sacrificial oxide in buffered HF.

## TESTING AND RESULTS

Tests have been performed to evaluate the feasibility of the microconnection approach and to determine the electrical and thermal behavior of the devices before, during, and after bonding. To facilitate thermal testing, the microconnection structure includes serpentine polysilicon resistors on the suspended p<sup>++</sup> island. These resistors can be configured in a full or half bridge configuration for monitoring the temperature of the pad area. Also, the interdigitated regions of each metal contact pad are separately accessible via wire-bond pads, which can be probed or bonded to the leads of a test package.

The ability to detect contact between cable leads and contact pads on the substrate is critical. To test the detection scheme, a lead tab on a cable is lowered onto a contact pad, and the 10MHz impedance between the interdigitated pad regions is monitored. As the cable lead tab approaches and then touches the contact pad, the magnitude of the impedance decreases significantly due to the increased series capacitance through the tab. When the cable is far away from the pads, the impedance between the two pad regions at 10MHz is 23k $\Omega$ ; as the lead tab contacts the pad, the impedance decreases to 1.9k $\Omega$ . These results closely match calculations for the capacitance change caused by moving the tab from an infinite distance to close contact (with the final capacitive gap defined only by a thin native oxide on the lead tab). This impedance change can be used as an electrical signature for the tab touch-down sequence, enabling automatic triggering of the heater.

After the lead tabs are in contact with the pads, the connection mechanism itself can be evaluated by pulse heating the structure while the island temperature and the electrical impedance between the contact regions of the metal pads are monitored and displayed on a digital storage oscilloscope. The results are plotted in Figure 6. For initial testing, a single pulse of 8V is applied to the heater for 1

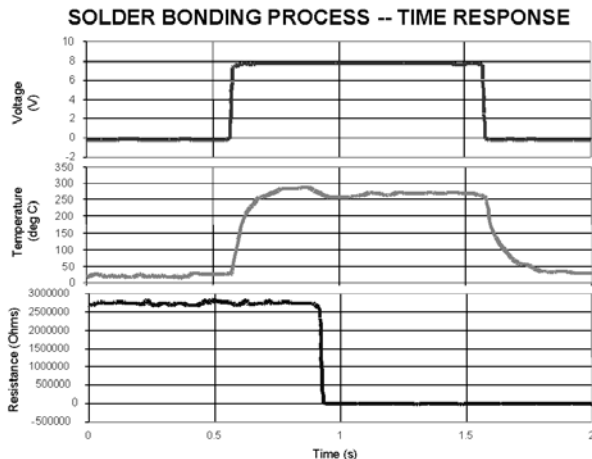


Fig. 6: Curves of input voltage, temperature, and pad resistance vs. time during the bonding process.

second. The island temperature quickly increases from room temperature to 285°C, causing the solder on the lead tabs to melt. The molten solder provides a low-impedance path ( $< 10\Omega$ ) between the interdigitated pad regions and between the pad and the lead tab. This process occurs in approximately 350ms. When the current pulse ends, the island cools and causes the solder to harden. Measurements of the steady-state power required to heat the pad with and without the cable present show heating efficiencies of 1.3mW/°C and 2.0mW/°C, respectively. The solder forms a secure mechanical and electrical bond between the lead tab and the contact pad. Figure 7 shows a photograph of a multi-lead cable bonded to a contact pad. Pads have been bonded on 100 $\mu$ m, 200 $\mu$ m, and 400 $\mu$ m centers. Although the mechanical strength of the stress-compensated dielectric windows has been adequate for the structures explored thus

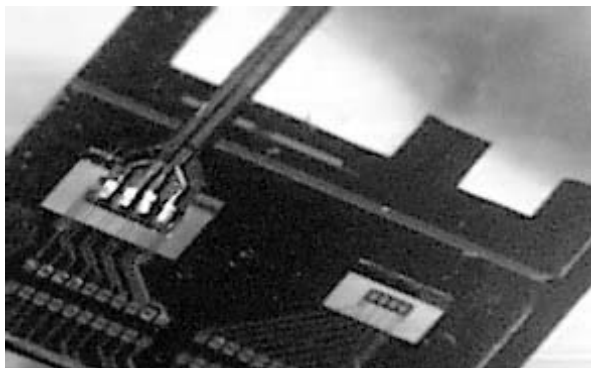


Fig. 7: Photograph showing two connection areas on a silicon substrate, one with a bonded polyimide cable.

far, using oxidized porous silicon plugs built into the bulk substrate would reduce the structure's fragility while retaining much of its thermal isolation.

## CONCLUSIONS

Localized solder-bonding has been used successfully to create bonds between miniature flexible cables and silicon microsystem platforms. Multi-lead contact to the pads can be detected automatically, triggering an embedded heater to initiate solder melting. This approach enables delicate microstructures to be connected and disconnected from microsystem platforms in the field, and is implemented with a process that is compatible with monolithic integration of circuits. This technology should contribute significantly to the miniaturization of microsystems with multiple off-board components.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] T.E. Moore, S.B. Crary, D.E. Koditschek, and T.A. Conklin, "Directed Locomotion in Cockroaches: 'Biobots'," *Acta Entomologica Slovenica*, December 1998, pp. 71-8.
- [2] P. Mohseni, K. Nagarajan, B. Ziaie, K. Najafi, and S.B. Crary, "An ultralight biotelemetry backpack for recording EMG signals in moths", *IEEE Transactions on Bio-Medical Engineering*, Vol. 48, Issue 6, June 2001, pp. 734-7.
- [3] Y.T. Cheng and L. Lin, "Localized bonding with PSG or indium solder as intermediate layer," *MEMS 1999*, pp. 285-9.
- [4] Intel Corporation, *Intel Flash Memory Chip Scale Package User's Guide*, 1999.
- [5] K.F. Harsh, V.M. Bright, and Y.C. Lee, "Study of micro-scale limits of solder self-assembly for MEMS," *Electronics Components & Technology Conference, 2000 Proceedings*, pp. 1690-5.
- [6] D.J. Anderson, K. Najafi, S.J. Tanghe, D.A. Evans, K.L. Levy, J.F. Hetke, X. Xue, J.J. Zappia, K.D. Wise, "Batch fabricated thin-film electrodes for stimulation of the central auditory system," *IEEE Transactions on Biomedical Engineering*, Vol. 36, Issue 7, July 1989, pp. 693-704.
- [7] J.F. Hetke, K.Najafi, and K.D. Wise, "Flexible Miniature Ribbon Cables for Long-Term Connection to Implantable Sensors," *Sensors and Actuators, A21-A23*, 1990, pp. 999-1002.
- [8] J. B. Yoon, C. H. Han, E. Yoon, and C. K. Kim, "Novel two-step baking process for high-aspect-ratio photolithography with conventional positive thick photoresist," *MEMS 1999*, pp. 316-318.